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An experimental investigation of Thermo acoustic refrigeration system using polynamide nylon 6 as stack material with helium gas

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ABSTRACT

Thermoacoustic refrigeration systems are attractive due to their simplicity, lack of moving parts, and potential for using environmentally friendly working fluids. In this study, we experimentally investigated the use of helium as the working gas into the TAR, intending to improve its performance. We designed and built a test rig consisting of a thermoacoustic resonator, a heat exchanger, and a loudspeaker to drive the system. Nylon 66 sheets is used to make three parallel stacks of mainly spiral, parallel and honeycomb. Helium is used as working fluids. The trials were conducted at a frequency of 500 Hz. The typical range for the working pressure is observed to be within 6 to 10 bar, while the average cooling load falls within the range of 2 to 10 W. The performance of a thermoacoustic refrigerator is investigated in relation to coefficient of performance (COP) and temperature differential. These variables include operating pressure, working frequency, and cooling load. The findings indicate that the use of helium in TARs can enhance performance and may have applications in refrigeration and cooling technologies.

KEYWORDS : Thermoacoustic refrigeration, Operational parameters, performance.

Statements and Declarations:

Competing Interests: No conflicts of interest are associated with this publication. All authors have reviewed and provided their approval for the final version of the article.

SYMBOLS, ABBREVIATIONS AND UNITS

COP-Coefficient of performance

DC- Direct current

LDA- Laser Doppler anemometry

SPAR- Space thermoacoustic refrigerator

TAR- Thermoacoustic refrigeration

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I. INTRODUCTION

Thermoacoustic refrigeration (TAR) is characterized by the generation of temperature differential through the propagation of sound waves [1]. Creating a stationary acoustic wave in a resonant chamber causes the compression and expansion of a working fluid, such as helium or air. [2]. Because it has the potential to revolutionize the refrigeration and cooling industries, thermoacoustic refrigeration has recently gained a lot of interest [3]. The compression and expansion cycle creates a temperature difference between the heated and cold extremities of the resonator, which can be used to drive a cooling cycle [4]. In terms of reliability and ease of upkeep, this makes it better than traditional refrigeration systems, which use mechanical parts like compressors and turbines [5]. The thermoacoustic refrigeration advantages include its simplicity and lack of moving elements [6]. In addition, thermoacoustic refrigeration may make use of working fluids that are kind to the environment, such as helium or air, which, in contrast to conventional refrigerants, do not contribute to the pollution of the natural environment [7].

Thermoacoustic refrigeration devices can operate at low temperatures and be efficient. They can cool electronics, medical gadgets, and food. Furthermore, because TARs do not have mechanical components, they are quieter than standard refrigeration systems, which is advantageous in areas where noise levels must be kept to a minimum [8]. Despite its benefits, thermoacoustic refrigeration is still experimental, and obstacles must be overcome prior to its widespread adoption. Achieving high levels of efficacy is one of the greatest obstacles, which necessitates optimizing system design and operation. Finding affordable production methods for the system's resonator and other components is another difficulty [9]. Simple, reliable, and environmentally friendly, thermoacoustic refrigeration could replace existing refrigeration systems. Thermoacoustic refrigeration could become a widely adopted technology for a variety of cooling applications if additional research and development are conducted [10].

The choice of working fluid has a significant impact on the efficacy of TARs. Due to its exceptional properties, helium is an essential working fluid in TARs [10]. Helium is a noble gas that is chemically inert, non-toxic, and non-flammable, which makes it a great choice for use in cooling systems. Helium's lower molecular weight implies a high acoustic power density and higher sound speed, which can enhances TAR efficiency [11]. The working fluid in TARs experiences expansion and compression as a result of the sound wave. The temperature difference between cold and heated ends of a resonator be able to driving of the cooling cycle. The system efficiency is affected by a working fluid's thermal conductivity, specific heat, and viscosity [12]. The lower specific heat of helium permits it to efficiently release and absorb heat, which improves heat transfer and increased cooling ability [13].

The helium as the operational gas in TARs is beneficial because of its low thermal conductivity [14]. This suggests that helium possesses a lower heating transfer capacity, rendering it a necessary choice for resonator. Because lower thermal conductivity, efficiency of helium improves by limiting the amount of heat that is lost from the hot end to the cool end [15]. The utilization of helium as the operational gas in TARs holds significance owing to its distinctive characteristics that have the potential to enhance the overall efficacy and effectiveness of the system. The low molecular weight, high sound speed, and lower thermal conductivity and specific heat of helium make it an attractive choice of TARs working fluid.

Approximately a century ago, people began toying with the idea of thermoacoustics. Rott, (1980) who specialised in quantitative thermoacoustics, were responsible for the development of intelligent thermoacoustic modern engines. Additionally, the investigative and hypothetical foundation for thermoacoustic refrigerators and heat pumps was constructed. Thermoacoustic refrigeration using high amplitude resonant soundwaves has been created by [1]. Poese & Garrett, (2000) using the DELTAE computer model, measured high-amplitude driven TAR and compared it to a 30W space thermoacoustic refrigerator (SPAR). [18] conducted research and he discovered that the optimum working gas ought to have a lower prandtl number and a bigger value of the ratio of specific heats. This was one of the findings of his study. Research on optimising the design of TAR using a method known as shortstack boundary layer approximation was described by Wetzel & Herman, (1997). Nanoparticles have wide range of applications in engineering applications [20]. Laser Doppler anemometry (LDA) was used by Bailliet et al., (2000) in their analytical investigation to determine the velocities of individual particles, and a microphonic pressure instrument was ustilized for determining quantity of acoustic power flowing through a TAR's resonator tube. The design strategy for the TAR has been detailed by [22], and it involves a theory of linear thermoacoustics. They have outlined the steps involved in creating a thermoacoustic cooler, as well as discussed how to optimise the design and development process. To test their theoretical prediction, A standing wave TAR was modelled and simulated by Tang et al., (2005) and looked at how the length of the resonance tube affected the efficiency of a thermoacoustically powered pulse fridge. With 2200W of heating load and an optimal resonator tube length, they found 88.6 K lowermost refrigeration temperature.

Tu et al., (2005) have conducted both theoretical and experimental research on the frequency specifications of a loudspeaker-driven TAR. Abakr et al., (2011) built and tested their TAR system, they discovered that a square wave pattern can produce a more effective cooling effect than other wave patterns. For the purpose of maximising performance, Herman & Travnicek, (2006) described a methodical and comprehensive design strategy for TAR design calculations, as well as a few thermodynamic and heat transport related concerns. We also explore two distinct optimization criteria to illustrate the intricacy of the optimization process. They have described the layout, built each component of the fridge in detail, and gone over the process for making the gas combinations. The cold heat exchanger was measured to be 65 degrees below zero, the coldest temperature ever recorded. The researchers also looked at how changing thermoacoustic characteristics, including the prandtl number and stack plate spacing, affected TAR efficiency. Four different stack geometries and three circular stacks have been examined by Ramesh Nayak et al., (2017) in terms of the impact of stack geometry on the performance of thermoacoustic refrigerators under different operating conditions. Using helium as the working fluid, they conducted trials and observed a maximum temperature differential of 19.4oC for a parallel plate stack cooling a 2W load at 400 Hz. They also found that the temperature differential between the plates in a parallel stack was greater than that in a circular stack. Thermoacoustic refrigeration using 10W cooling power was built and analysed [28] utilising DeltaEC software. The results of the software optimization of the quarter-wave length resonator design were compared with previously published, optimised findings. About a 201 percent increase in power density and a 9 percent increase in COP were found to be the results of this investigation. For two working fluids, air and helium, at working pressures up to 10 bar, Ghorbanian & Karimi, (2014) have developed and manufactured 10W cooling load TAR. They reported a COP of 2.5 after optimising the stack. As a means of decreasing the acoustic losses in the resonator tube, they adjusted the D2/D1 diameter ratio to 0.43. Using the DeltaEC programme, [30] investigated stack-based TAR. Their analysis has centred on how changes in mean operating pressure and other parameters affect the device's functionality. Cooling capacities of 1W to 10W at operating pressures up to 10bar were simulated for the thermoacoustic refrigerator. Additionally, Arya et al., (2018) conducted research on effect that dynamic pressure has upon the performance of TARs, and they came to the conclusion that mean operating pressure has a direct influence on the performance in terms of generating cooling capacity and T. The researchers came to this conclusion after coming to the conclusion that dynamic pressure has an impact on the performance of TARs. Aluminum with a 2 mm polyurethane coating within the resonator was used to create the experimental setup, which significantly reduced heat losses to the surrounding air. For driving ratios between 0.6% and 1.6%, they analysed how the cooling load affected COP for TAR.

Numerical and theoretical studies of thermoacoustic refrigerator performance have been the focus of a great deal of academic effort, as is evident from a review of the relevant literature. However, there has been very little effort done experimentally. Most of these experiments, however, suffered from the inevitable conduction heat losses associated with their metal resonator systems due to their fabrication from aluminium and other metals.

The aim of the present investigation is to assess the efficacy of a Thermal Energy Storage and Retrieval (TAR) system that employs helium as the working medium, and to contrast its performance with that of earlier studies that employed air or nitrogen. TARs have the potential to outperform traditional refrigeration systems in dependability, simplicity, and environmental friendliness. The choice of working fluid, however, has a significant impact on how well TARs perform. Through a thermal acoustic refrigerator's (TAR) efficiency assessment of utilizing helium as a working medium, this investigation can offer valuable perceptions on advantages derived from utilization of helium in TARs. The study could improve refrigeration and cooling systems. Helium may improve TAR performance, allowing for more efficient and environmentally friendly cooling systems. Additionally, study could provide a better understanding of the affecting factors on efficacy of TARs, which could be used in the future to optimize the design and operation of these systems.

II. SPECIFICATIONS OF THE EXPERIMENTAL SETUP AND EXPERIMENTATION PROCEDURE

Figure 1 shows the Hofler Thermoacoustic Refrigerator. It comprising of a resonator, a heat exchanger, and a stack of plates or screens. The resonator is a cylindrical conduit composed of a rigid substance, such as metal, which is hermetically sealed at both extremities and contains a functional medium, such as helium or air. The heat exchanger is in thermal contact with resonator's hot and cold ends utilized for transmitting heat to or from the working fluid. The plates stack is inside the resonator. The compression and expansion process results in the generation of heat. The stack of plates or screens is made of a high thermal conductivity material like copper, and it is designed to maximize the surface area of the plates for heat transfer. A transducer is utilized for generating a stationary waveform within the resonator. The working fluid is compressed and expanded by this standing wave. The compression cycle process induces thermal energy transfer to the working fluid as it passes through the heat exchanger situated at the high-temperature end of the resonator. In expansion process, the working fluid faces a decrease in temperature due to passing through heat exchanger at cold end of the resonator. During compression and expansion cycles, heat is stored and released by stacks of plates inside a resonator, which increases the system's efficiency. By generating a standing wave in a resonator, as in Hofler's thermoacoustic refrigerator, the working fluid is subjected to periodic compression and expansion. Using a regenerator, like a stack of plates or screens, makes the system more efficient. This makes it a promising device for refrigeration and cooling applications.

The central location of the stack within the thermoacoustic refrigerator. The stack facilitates the transfer of heat within the closed resonator tube's inert gas environment through a pumping mechanism. On both ends of the stack, heat exchangers are employed for support. Copper hollow tubes with diameters of 2 and 4 millimeters are used to build the heat and

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cold exchangers. The utilization of copper mesh, with a thickness of 0.6 mm and a porosity ratio of approximately 80%, enhances the heat transfer between the two heat exchangers. The structural components of the thermoacoustic refrigerator, such as the resonator, are built out of nylon 66 because of its insulating characteristics and the ease with which it can be manufactured.

The experimental configuration of a thermoacoustic refrigerator typically comprises various components, such as the resonator, heat exchanger, regenerator, and driver, as illustrated in Figure 1. To contain the working fluid and produce a standing acoustic wave, the working fluid is placed inside a tube or chamber composed of a stiff material, like metal or ceramic. The resonator will normally have two ends, referred to as a hot end and a cold end, and will typically be sealed to prevent the working fluid from escaping. To either add or remove heat from the working fluid, a heat exchanger is required. A typical thermoacoustic refrigerator is made up of two heat exchangers at the hot and cold ends of the resonator. Typically made up of a high thermal conductivity substance like copper to maximize heat transfer. The regenerator is located within resonator to amass and release thermal energy during the expansion and compression stages. The regenerator is made up of permeable medium like ceramic or wire mesh, which has been designed for exhibiting a significant surface area to thermal conduction improvement. The driver generates a constant resonator acoustic wave. The driver for a thermoacoustic refrigerator may be a piezoelectric device, loudspeaker, or mechanical oscillator on the basis of design. The measurement and control system tracks the thermoacoustic refrigerator's performance. This system typically contains sensors to measure temperature, pressure, and flow rate and a computer or other device to evaluate and store the data.

Figure 1: Experimental Setup of Thermoacoustic Refrigerator

Thermoacoustic refrigeration technology has gained considerable attention in light of its environmentally sustainable and energy-efficient cooling capabilities. Numerous research have been carried out to examine the performance traits of various stack geometries in the quest to enhance its performance. The various geometries that exist include spiral stacks exhibiting a honeycomb structure, circular stacks, and parallel plate stacks. The objective of the studies is to identify the most effective stack configuration for achieving optimal performance with respect to minimizing the noise, maximizing a cooling power, and enhancement in efficiency. To investigate further the effect of gap size and porosity ratio on thermoacoustic refrigeration performance, a stack of Nylon 66 sheets is constructed. Figure 2 graphically depicts the designs of the stack. The performance of these stacks is evaluated by changing the mean operating pressure, cooling load, drive ratio, and operating frequency. This research provides valuable insights into effect of gap size and porosity ratio upon performance of TARs. By understanding the underlying principles and mechanics, researchers can develop better designs that can improve the efficiency and reliability of thermoacoustic refrigeration technology.

(a) Spiral shaped (b) Parallel plate (c) Honeycomb

Figure 2: Various Stack geometries used in Thermoacoustic Refrigerator

Experiments are carried out taking into account various operating circumstances for different stack geometries to examine an influence two subsequent plates spacing of a stack on the thermoacoustic refrigerator performance with respect to temperature differential. By adjusting the regulating system, the thermoacoustic refrigerator's resonating system may be pressurised to a range of 6 bar to 10 bar, making it suitable for use with helium, argon, and their mixtures. For all test measurements, the necessary operating frequency was set to 500 Hz. The cold heat exchanger is connected to a resistance heating coil that is powered by a 5A30V DC power supply unit. Every trial begins with the system being stabilised by keeping the operating pressure at a constant, following which the data is captured. Different levels of average operating pressure, cooling load, operating frequency and driving ratio are tried in each experiment. In order to test a thermoacoustic refrigerator, one must first fill the unit with working gas at the required pressure, turn on the thermocouple module, audio frequency oscillator, amplifier, and data acquisition system, fill the water tank with cooling water and regulate the flow rate, switch on the regulated DC supply to the heater up to the required heat load, set the required frequency on the audio frequency oscillator, set the required power in the amplifier to achieve r, and finally fill the unit with working gas at the required.

III. RESULTS AND DISCUSSION

Figure 3 presents graphical representation of relationship between cold end temperature and pressure at a frequency of 500 Hz for different stack configurations. The results show that the temperature variation in the Spiral, Parallel, and Honeycomb structures ranges from 12 to 25, 15 to 28, and 8 to 22 degrees Celsius, respectively. The highest temperature of 28 degrees Celsius was observed for the Parallel structure at a pressure of 6 bar, while the lowest temperature of 8 degrees Celsius was observed for the Honeycomb structure at a pressure of 10 bar. These findings suggest that the Honeycomb structure performs better in maintaining low temperatures at higher pressures, while the Parallel structure is more efficient at higher temperatures and lower pressures.

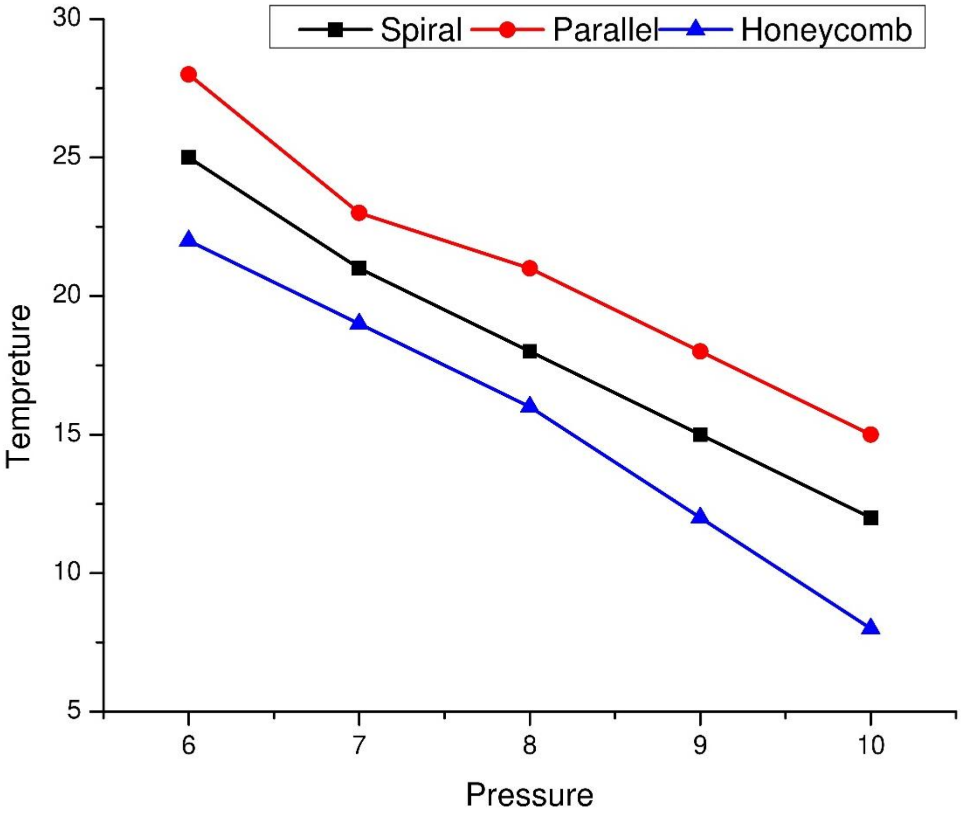

Fig. 3 Temperature vs pressure at cold end of stack at 500 Hz frequency for different stack geometry.

The experimental findings suggest that, when subjected to various stack geometries and cooling load levels, the honeycomb configuration yields the most minimal cold end temperature in comparison to alternative geometries. This suggests that honeycomb structure could be a promising option for enhancing the efficacy of TARs.

Figure 4 depicts the variation of temperature difference between the hot and cold ends of the stack with respect to pressure, while maintaining a constant cooling load and frequency. According to the findings, the largest temperature difference occurs within the investigation's pressure range, or at a pressure of about 4 bars. When the pressure is raised past this point, the temperature difference starts to go down, which means that pumping more air into the system won't make it cooler. The results indicate that there exists a specific pressure range that is most effective in attaining the highest temperature differential in thermally activated refrigerators (TARs). Understanding this pressure range can assist engineers in optimizing the design and operation of these systems, increasing efficiency and efficacy. These findings illuminate thermoacoustic refrigeration's mechanics and can help enhance its design.

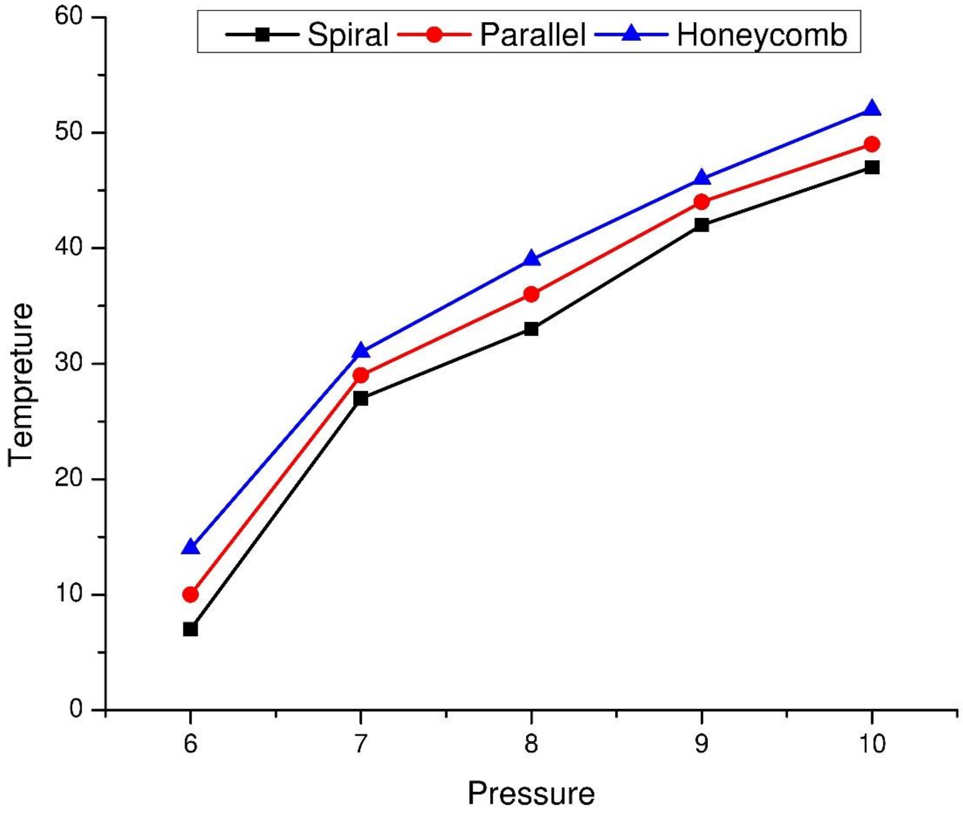

Fig. 4 Temperature vs pressure at cold end of stack at 500 Hz frequency for different stack geometry

Figure 5 illustrates relationship between cooling load and temperature differential between hot and cold ends of the stack. The graphical representation illustrates a linear correlation between the cooling load and temperature gap. This suggests that an increase in the cooling load within the system is linked to a corresponding rise in the temperature gap between the hot and cold sides of the stack. The graph also displays the ranges of uncertainty that were found when evaluating the cooling load. The aforementioned ranges serve to illustrate the degree of imprecision linked to the measurements and computations employed in ascertaining the cooling load. In spite of these unknown factors, the graph demonstrates that there is a distinct and robust linear relationship between the cooling load and the temperature gap.

The implications of these findings are noteworthy in terms of the development and implementation of Targeted Advertising Regulations (TARs). Engineers can maximize the efficiency and effectiveness of these systems by gaining a deeper understanding of the connection between cooling load and temperature gap. The present study offers significant contributions to the underlying principles of thermoacoustic refrigeration and can potentially guide the advancement of more efficient designs for this nascent field.

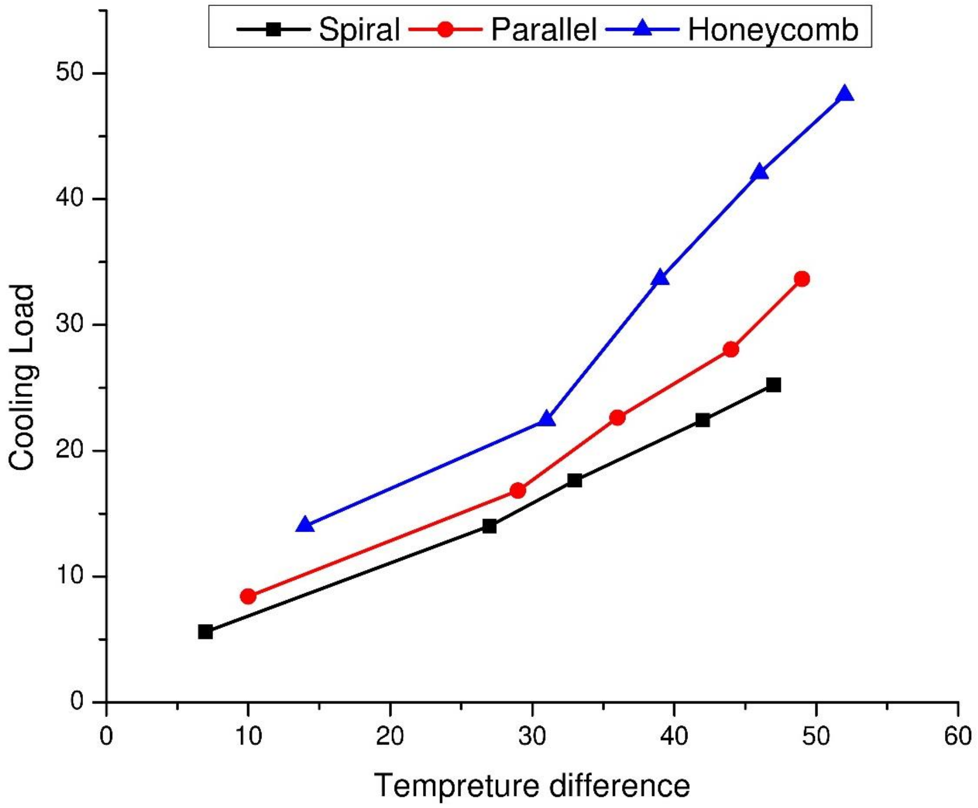

Fig. 5. Temperature difference versus Cooling load in ends of stack

The graphical representation depicted in Figure 6 illustrates the correlation between pressure and cooling demand, specifically at a frequency of 500 Hz. The graph shows a linear relationship between pressure and cooling demand, which could be because the gas in the system is oscillating. In the context of the inquiry, it has been determined that a correlation exists between the maximum temperature differential across the stack's hot and cold ends and a corresponding frequency. The aforementioned outcome implies that enhancing the frequency of the system has the potential to yield noteworthy enhancements in its overall performance. Engineers will be able to better optimize the design and operation of TARs by gaining a better understanding of the link between pressure, cooling requirement, and frequency. Through the identification of the optimal frequency, it is possible to attain the highest temperature differential and cooling efficiency. These results offer important new understandings of the thermoacoustic refrigeration mechanism and can help in the creation of more effective designs for this new field of engineering.

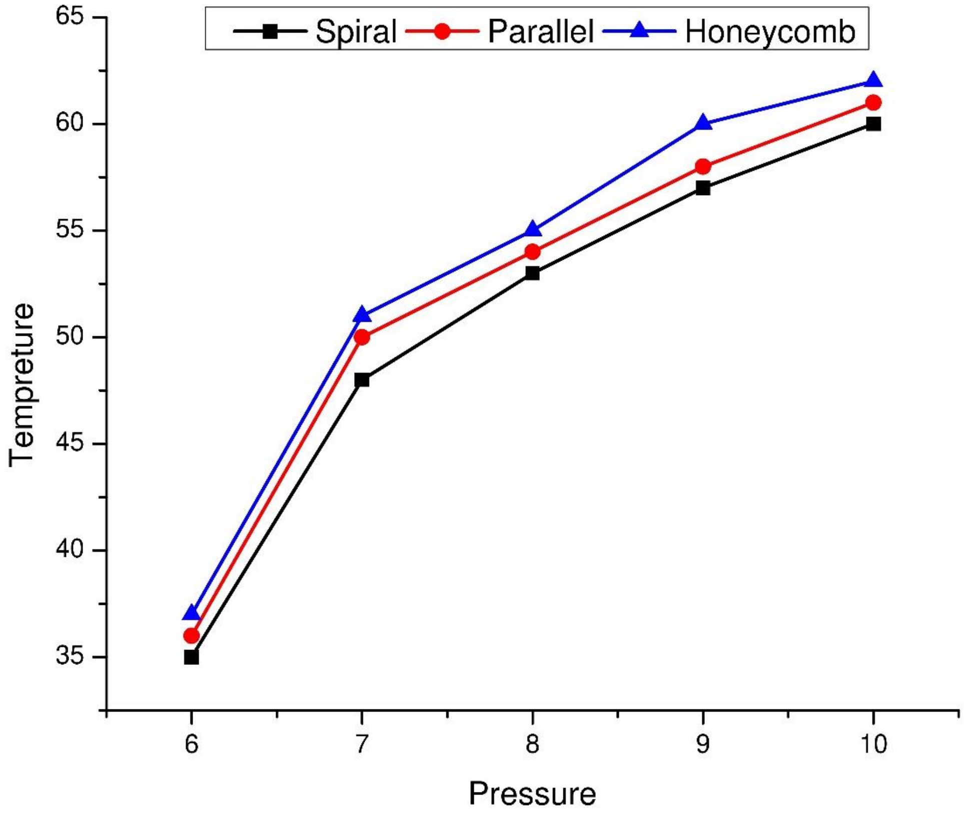

Fig. 6. Temperature difference versus Cooling load for different stack geometry

The graphical representation depicted in Figure 7 elucidates the correlation between the mean performance coefficient (COP) of the thermal energy storage system with auxiliary refrigeration (TAR) and the charging pressure. During the course of the testing, a honeycomb stack was capable of reaching a maximum COP value of 0.43. The findings indicate that the coefficient of performance (COP) of the system changes in response to changes in the charging pressure.

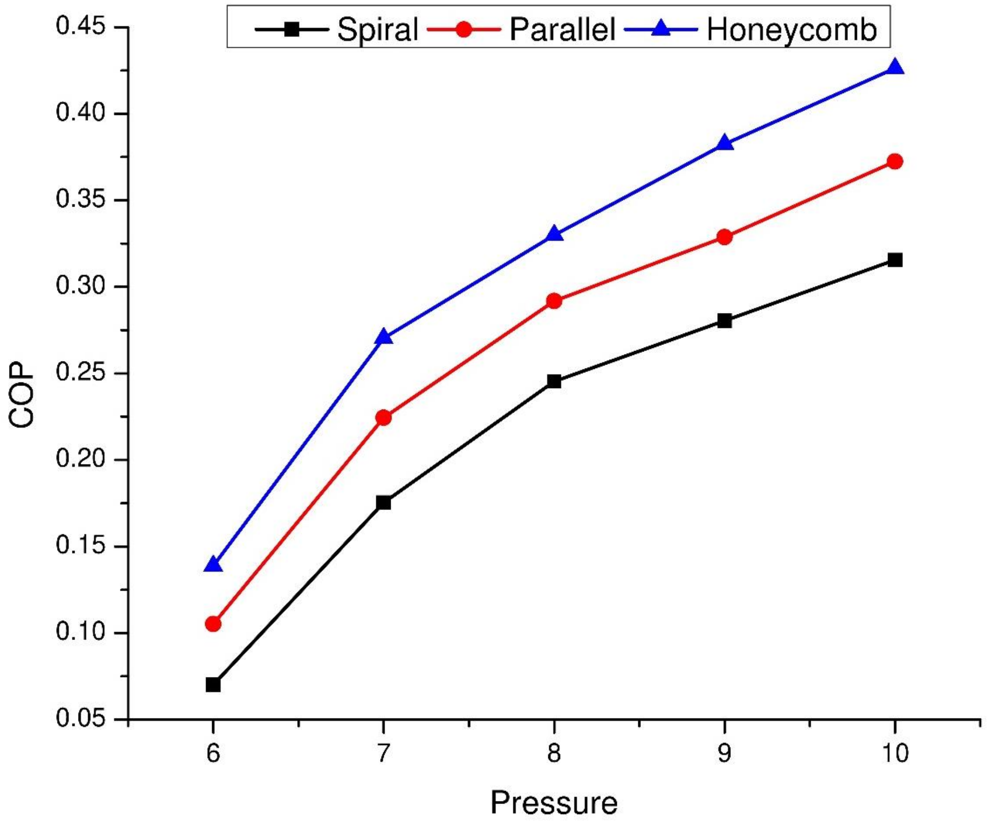

Fig. 7. Effect of charging pressure on COP for different stack geometry

Although the coefficient of performance (COP) of 0.43 may appear relatively inferior in comparison to that of a conventional vapor compression refrigeration system, it is crucial to acknowledge that thermoacoustic refrigerators (TARs) possess distinct performance attributes and are currently in their nascent phase of advancement. Vapor compression systems' COP range is often smaller than thermoacoustic cooling systems'.

However, the attainment of a coefficient of performance (COP) of 0.43 represents a noteworthy accomplishment for a thermal absorption refrigeration (TAR) system, underscoring the capacity of this technology to furnish cooling solutions that are both energy-efficient and ecologically sound. Additional investigation and advancement may enhance the efficacy of said systems and move them nearer to attaining commercial feasibility. These findings provide vital information about TAR performance and its promise as a sustainable alternative to standard cooling systems.

IV. CONCLUSION

The experimental investigation on performance improvement of TAR using helium involved testing the system. To control the cooling load, resistance heating was utilized in place of cold side heat exchanger.

The findings of study indicated a positive correlation between the temperature differential of the hot and cold ends of the stack and the cooling load, with the latter increasing as the former increases. This implies that attaining a significant temperature differential is required for TARs for higher cooling efficiency.

Furthermore, the research revealed the elevated pressure in isolation does not invariably lead to significant variance in cooling temperature which reflect in a heightened cooling burden. The stack geometry is also an important aspect to determine the system's efficiency. It is imperative that the stack's design is optimized for attaining the intended performance attributes.

Among the various stack geometries, a honeycomb configuration exhibited the most elevated COP value of 0.43. This number is notable as it reflects the highest COP during the studies and illustrates the capability of thermoacoustic refrigeration technology to deliver cost-effective and environmentally friendly cooling solutions.

The present research offers significant contributions to the understanding of the performance attributes and enhancement of Thermal Actuated Resonators (TARs) utilizing helium. The research findings can help in the creation of cooling systems that are more dependable and efficient in order to satisfy the rising demand for environmentally friendly and sustainable cooling technologies. Researchers and engineers may design and build TARs with high cooling efficiency, reliability, and sustainability by studying the mechanics and finding the best working conditions.

Prospective investigations may enhance the effectiveness and dependability of thermal energy storage systems by examining the influence of diverse operating fluids, evaluating various materials, refining the stack configuration, devising novel cooling load management techniques, and scrutinizing diverse operational parameters. These findings can aid in maximizing cooling efficacy and dependability, bringing TARs closer to commercial viability as a sustainable and eco-friendly cooling technology.

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